3D FE Modelling of Interlamination Short-circuits Taking into Account the Building Bar

J. L. Müller[1], A. Benabou[2], T. Henneron[2], F. Piriou[2], J. P. A. Bastos[3], J-Y. Roger[1]
EDF R&D[1], L2EP - LAMEL[2], GRUCAD[3]
EDF, 1 avenue du Général de Gaulle - 92141 Clamart, France
L2EP, Université Lille1 – Nord de France - 59655 Villeneuve d'Ascq, France
GRUCAD, CTC – UFSC, CP. 476 - 88040-970 - Florianópolis – SC, Brasil
juliana-luisa.muller@ed.univ-lille1.fr

Abstract — This paper deals with the modelling of a lamination stack, crossed by a conducting building bar, in the presence of an inter-lamination short-circuit. Under a time-varying magnetic flux, an induced current loop flows through both the building bar and the fault. To reduce computational times, a homogenization technique is used to model the lamination stack. Eddy current losses and total magnetic energy values are compared for cases with and without homogenization for 50 Hz and 100 Hz.

I. INTRODUCTION

Turbogenerator stators are subjected to interlamination short-circuits. The faults create eddy current loops which cause local heating in the stator and have impact on the magnetic flux distribution in the yoke. This may decrease the performances of the machine and cause, in more severe cases, irreversible damages to the magnetic circuit. To detect these faults and prevent the damages, an experimental method, the EL CID (ELectromagnetic Core Imperfection Detector) [1, 5] is used. It consists in exciting the stator at 3% to 4% of its nominal magnetic flux. In the presence of a short-circuit in the lamination stack, the magnetic field produced by the fault current is detected. Experience shows that faults are well detected especially when located near a tooth surface. Therefore, the main objective of this work is to provide a numerical tool that allows investigating the fault current in relation with the corresponding EL CID signal.

In that context, the numerical study of a turbo-generator stator is not trivial as it presents dimension scales varying from the micrometer (thickness of the insulating varnish between laminations) to the meter (stator radius). This is the reason why an adapted numerical approach should be applied, such as a homogenization technique. In this communication, the work focuses on the modelling of a lamination stack with a short-circuit.

II. MAGNETODYNAMIC FORMULATIONS

The studied domain is denoted *D* with its conducting part D_c (non homogenized laminations, electrical fault and building bar), non-conducting part D_n and non-conducting homogenized domain D_h (homogenized laminations). In the frequency domain magnetodynamics, Maxwell's equations and behaviour laws may be written,

$$\mathbf{curl}\,\mathbf{E} = -\mathrm{j}\omega\mathbf{B} \quad \text{(a)} \qquad \mathbf{curl}\,\mathbf{H} = \mathbf{J}_S + \mathbf{J}_{ind} \quad \text{(b)} \qquad (1)$$

$$\operatorname{div}\mathbf{B} = 0 \quad \text{(a)} \qquad \operatorname{div}(\mathbf{J}_S + \mathbf{J}_{ind}) = 0 \quad \text{(b)} \qquad (2)$$

$$\mathbf{B} = \mu_0\,\mu_r\,\mathbf{H} \quad \text{(a)} \qquad \mathbf{J}_{ind} = \sigma\,\mathbf{E} \quad \text{(b)} \qquad (3)$$

with **E** the electric field, **H** the magnetic field, **B** the magnetic flux density, $\mathbf{J}_s$ the source inductor current density, $\mathbf{J}_{ind}$ the eddy current density, ω the pulsation, μ_r the relative permeability, μ_0 the air magnetic permeability and σ the electrical conductivity. On Fig. 1, **n** is the outward unit normal vector.

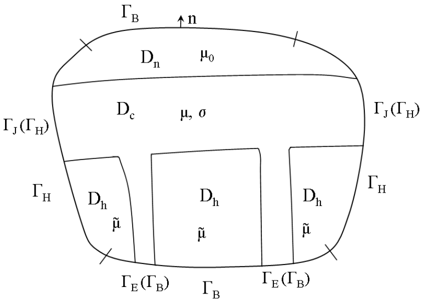

Fig. 1. Studied domain

To ensure the uniqueness of the solution, the following boundary conditions are applied on respectively Γ_B and Γ_H,

$$\mathbf{B}\cdot\mathbf{n} = 0 \quad \text{on } \Gamma_B \quad \text{(a)} \qquad \mathbf{H}\times\mathbf{n} = 0 \quad \text{on } \Gamma_H \quad \text{(b)} \qquad (4)$$

For the conducting domain, the following boundary conditions are applied,

$$\mathbf{J}_{ind}\cdot\mathbf{n} = 0 \quad \text{on } \Gamma_J \quad \text{(a)} \qquad \mathbf{E}\times\mathbf{n} = 0 \quad \text{on } \Gamma_E \quad \text{(b)} \qquad (5)$$

The conditions (5) may be applied simultaneously with conditions (4), as shown in Fig. 1 (conditions in parentheses).

A. Magnetic formulation

In this formulation, an electric vector potential **T** and a magnetic scalar potential Ω are introduced,

$$\mathbf{J}_{ind} = \mathbf{curl}\,\mathbf{T} \qquad (6)$$

$$\mathbf{H} = \mathbf{H}_s + \mathbf{T} - \mathbf{grad}\,\Omega \qquad (7)$$

With $\mathbf{H}_s$ the magnetic source field related to the inductor. Then, using relations 1(a) and 2(a), the weak formulation to be solved is obtained. In order to impose a magnetic flux, an equation is added to the system. This is described by [2].

B. Electrical formulation

In this formulation, a magnetic vector potential, **A**, and an electric scalar potential, φ, are introduced. Thus, the magnetic induction and the electric field can be written,

$$\mathbf{B} = \mathbf{curl}\,\mathbf{A} \qquad (8)$$

$$\mathbf{E} = -j\,\omega\,\mathbf{A} - \mathbf{grad}\,\varphi \qquad (9)$$

From the relations 1(b) and 2(b), the weak formulation to be solved is deduced. To impose a magnetic flux, a supplementary source field is added to the definition of **E** and **B** [2, 3].

III. HOMOGENIZATION TECHNIQUE

The fault current is supposed to flow through the building bar, electrical fault and the laminations. This configuration has been validated by preliminary numerical calculations. Then, the homogenized region is composed of the three first sheets, counting from the symmetry plane (due to symmetry, only half of the system is modelled), the building bar and the electrical fault (see figure 2). This means that the homogenized region (laminations + insulating varnish) has been replaced by a non-conducting volume with an equivalent complex magnetic permeability [4, 5]. This one is written under the form,

$$\tilde{\mu} = \frac{12\mu}{12 - j\omega\mu\sigma d^2} \qquad (10)$$

Moreover, the laminations are made of grain-oriented steel which magnetic permeability has been obtained from Single Sheet Test (SST) measurements (μ_{rx}=15000 and μ_{ry}=2000). The relative permeability μ_{rz} is equal to 30 as given in [7]. The magnetic permeability tensor is used,

$$\|\mu\| = \begin{bmatrix} \mu_{rx}\mu_0 & 0 & 0 \\ 0 & \mu_{ry}\mu_0 & 0 \\ 0 & 0 & \mu_{rz}\mu_0 \end{bmatrix} \qquad (11)$$

Note that these values are extracted from the linear part of the average behaviour law. In fact, the EL CID test does not saturate the material. A reference model, without homogenization (sheets and insulating layers are modelled), is used to validate the proposed numerical approach.

IV. APPLICATION

The studied structure is composed of four ferromagnetic sheets (0.35mm thick), with a building bar and an electrical fault crossing through the lamination stack.

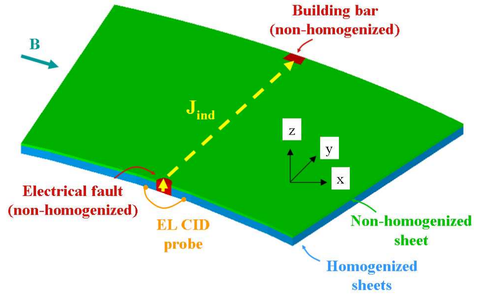

Fig. 2. Modelled structure

Results of the reference and homogenized models, in terms of eddy current losses in the fault (Table I) and total magnetic energy in the system (Table II), are compared for both formulations at frequencies 50 and 100Hz. The homogenized approach gives good results for the eddy current. In the case of the energy, results are acceptable. This can be explained by a coarser mesh in the laminations whereas the electrical fault and building bar, as they are the regions of interest, have a fine mesh. One can also observe that the current flowing through the electrical fault (Table III) is in good agreement between both formulations.

TABLE I
EDDY CURRENT LOSSES IN THE ELECTRICAL FAULT

	Reference values (W/kg)	Homogenized system values (W/kg)	Difference between homogenized and reference systems (%)
50 Hz A-φ	0.875	0.868	0.79
50 Hz T-Ω	0.865	0.853	1.39
100 Hz A-φ	2.737	2.740	0.10
100 Hz T-Ω	2.641	2.628	0.49

TABLE II
TOTAL MAGNETIC ENERGY

	Reference Values (J)	Homogenized Values (J)	Difference between homogenized and reference systems (%)
50 Hz A-φ	7.55E-07	6.58E-07	12.83
50 Hz T-Ω	7.75E-07	6.71E-07	13.44
100 Hz A-φ	1.03E-06	9.76E-07	5.43
100 Hz T-Ω	1.07E-06	1.02E-06	5.29

TABLE III
CURRENT IN ELECTRICAL FAULT

	Reference with fault (A)	Homogenized system with fault (A)
50 Hz A-φ	0.721	0.667
50 Hz T-Ω	0.775	0.671
100 Hz A-φ	1.037	0.984
100 Hz T-Ω	1.048	0.986

V. CONCLUSION

A lamination stack with an electrical fault and a building bar constituting a "yoke flux linkage" [6] has been modelled. A homogenization technique has been used, yielding a low error, especially in the electrical fault, which is the interest region. These results show that it is possible to model interlamination short-circuits despite the differences between implicated dimensions.

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